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Review

The Effects of Exergames on Muscle Architecture: A Systematic Review and Meta-Analysis

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Abstract: Muscle architectural parameters play a crucial role in the rate of force development, strength, and sports performance. On the other hand, deteriorated muscle architectural parameters are associated with injuries, sarcopenia, mortality, falls, and fragility. With the development of technology, exergames have emerged as a complementary tool for physical therapy programs. The PRISMA 2020 statement was followed during the systematic review and meta-analysis. CENTRAL, CINAHL, PROQUEST, PubMed, and OpenGrey databases were searched last time on 22 September 2021. In total, five controlled trials were included in the systematic review. Twelve weeks of virtual dance exercise (Dance Central game for Xbox 360[®]) showed a medium effect on the improvement of hamstrings ($g = 0.55$, 95% CI $(-0.03, 1.14)$, $I^2 = 0\%$) and the quadriceps femoris muscle cross-sectional area ($g = 0.58$, 95% CI $(0.1, 1.00)$, $I^2 = 0\%$) in community-dwelling older women. Additionally, a four-week virtual balance-training program (the ProKin System) led to significant increments in the cross-sectional areas of individual paraspinal muscles (14.55–46.81%). However, previously investigated exergame programs did not show any medium or large effects on the architectural parameters of the medial gastrocnemius muscle in community-dwelling older women. Distinct exergame programs can be used as a complementary therapy for different prevention and rehabilitation programs.

Keywords: exergame; fascicle length; muscle architecture; muscle thickness; cross-sectional area; pennation angle; serious game; systematic review; virtual



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1. Introduction

Muscle architecture is a comprehensive term comprising fascicle geometry (fascicle length and pennation angle) and muscle size (anatomical and physiological cross-sectional areas, muscle thickness, and muscle length) [1]. Larger muscle sizes are strongly associated with higher muscle strength [2–12]. Additionally, longer fascicle lengths and larger muscle sizes increase the rate of force development, power generation, and sprint and walking performances [10,13–22]. On the other hand, shorter fascicle lengths, smaller muscle sizes, and muscle size ratios are associated with sport and orthopaedic injuries of the lower extremity [23–32]. Furthermore, significant adverse alterations in the muscle size, fascicle length, and pennation angle occur due to ageing [33,34]. The decrements in muscle size and muscle functionality have been defined as sarcopenia [35,36], which is significantly associated with an increased risk of falling, and consequently mortality and morbidity in the elderly or people suffering from other health conditions [35,37–40]. Similarly, decrements in muscle size were also detected due to the disuse of muscles after bed rest [41,42] or exposure to microgravity [43]. These muscle atrophies might lead to reduced contractile performance and metabolic dysregulations [44]. Therefore, muscle architectural parameters should also be monitored during rehabilitation and prevention programs, such as the prevention of falls in the elderly or the prevention of hamstring injuries in athletes, etc.

Virtual games (exergames) have emerged as a complementary tool to enhance physical activity and exercise with the development of technology [45]. Due to its motivating and

interactive features, it has been stated that exergames might increase commitment to exercise [46–49]. Exergames, which mimic cycling, dancing, running, walking, playing a sport modality, and resistance training, have become commercially available [50–56]. Nowadays, exergames have been used in various rehabilitation programs for cerebral palsy, Parkinson’s disease, stroke, obesity, or sarcopenia [57]. A review article pointed out that using exergames in physical therapy resulted in similar improvements as with conventional therapy in most cases [57].

Numerous systematic reviews have focused on the effects of exergames on several outcomes, including anxiety level [53], balance [58–61], cardiac rehabilitation [62,63], childhood obesity [64,65], cognition [66–71], depression [70,72,73], exercise behaviour [74], motor skills [75–77], muscle strength [54], musculoskeletal pain [78], physical activity [32,79–81], postural control [82,83], psychological effects [84], quality of life [85], respiratory conditions [78], social effects [86], and walking capacity [87].

Despite the crucial importance of the muscle architectural parameters, however, there is no systematic review investigating the effects of exergames on skeletal muscle architecture in the literature. Exploring the impacts of exergames on the architecture of skeletal muscles can be a reference point for future directions of the development of exergames and rehabilitation programs for people who need improvements in muscle architectural parameters, such as the elderly, injured people, and patients exposed to long-term bed rest. Therefore, this systematic review aimed to examine studies investigating exergames-induced architectural alterations in the skeletal muscle architecture in humans, and to find out the effect size of exergames on the stimulation of improvements in the architectural parameters of individual muscles in humans.

2. Materials and Methods

The Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) 2020 statement [88] was used as the guideline of this review. The PRISMA 2020 checklist, which consists of a 27-item checklist and focuses on the introduction, methods, results, and discussion sections of a systematic review, is presented in the Supplementary Table S1. Before this review, a systematic review protocol was registered on INPLASY (INPLASY202140054) and is fully available online [89].

2.1. Information Sources

Cochrane Central Register of Controlled Trials (CENTRAL), CINAHL, ProQuest, PubMed, and OpenGrey databases were searched first on 10 April 2021 for all dates without applying a time limitation, and last on 22 September 2021. Additionally, reference lists of eligible studies were screened in order to avoid publication bias caused by grey literature as an addition to the OpenGrey database search. Database search histories are shown in the Supplementary Table S2.

2.2. Database Search Strategy, Eligibility Criteria, and Study Selection Process

Databases were searched by the first (N.S.) and second (G.Y.) authors, using a combination of the following key terms: (“Active video gaming” OR Avatar OR AVG OR “Commercial game” OR “Computer-based” OR “Computer based” OR “Computer feedback” OR “Computer game” OR “Dance dance revolution” OR “Digital game” OR “Digital-game” OR Exergam* OR “Game training” OR “Game exercise” OR “Game-based” OR “health game” OR IREX OR Kinect OR “Lower limb power rehabilitation” OR Nintendo OR “Play station” OR “Play-station” OR SensBalance OR “Serious game” OR “Serious gaming” OR “Sony EyeToy” OR “Video game” OR “Video-game” OR “Videogame” OR “Video gaming” OR “Video based” OR videobased OR “Video-based” OR “Virtual reality” OR VRT OR Wii OR Wobble OR Xavi* OR XBOX OR X-box) AND (“Muscle architecture” OR “Cross sectional area” OR “Cross-sectional area” OR Fascic* OR “Fiber length” OR “Fibre length” OR “Muscle length” OR “Muscle structure” OR “Muscle thickness” OR “Muscle volume” OR Pennat* OR Pinnat*).

The eligibility criteria included studies (1) investigating the effects of an exergame intervention; (2) presenting magnetic resonance imaging (MRI) or ultrasound measured alterations in one or more specifically defined muscle architectural parameter(s) as an outcome; (3) that were a full-text journal article; (4) written in the English language.

Duplicate records were removed by using the EndNote X⁹ computer program [90]. After the removal of duplicates, the remaining records were independently screened by the first (N.S.) and second authors (G.Y.) in a blinded status via Rayyan—a web and mobile app for systematic reviews [91]. Similarly, data extraction of the eligible studies was independently performed by the lead (N.S.) and second (G.Y.) authors. Disagreements about selecting the studies and extracting data were solved by discussion between the lead (N.S.) and second (G.Y.) authors, and the third author (T.Y.) was considered as referee in the case of unsolved disagreements. The first and second authors were blind to each other's decisions during the whole screening process. In the case of the absence of full-text versions of the articles, the articles were obtained by contacting the Bangor University and Tokyo Metropolitan University libraries.

2.3. Outcome Measures

Exergames-induced changes in the architectural parameters of individually defined muscles, including the anatomical cross-sectional area, fascicle length, muscle thickness, pennation angle, and the physiological cross-sectional area, were the constituted outcome measures of this systematic review.

2.4. Quality Assessment of Eligible Studies

The Downs and Black checklist [92], which consisted of a 27-item checklist, was used for quality of assessment of both non-randomised and randomised trials. This systematic review used the following classifications for the quality of evidence: 26–28 = excellent, 20–25 = good, 15–19: fair, and ≤ 14 = poor quality, based on the previous systematic reviews [93,94]. The first (N.S.) and second authors (G.Y.) independently assessed the quality level of the eligible studies. Any conflicts that arose with regard to the assessment of quality was solved by a discussion between the first and second authors, and the third author (T.Y.) was considered the referee for the unsolved conflicts. In addition to the quality assessment of eligible studies, the risk of bias of included studies was independently assessed by the first and second authors via The Cochrane Collaboration's tool for assessing the risk of bias in randomised trials [95]. Included studies were examined based on random sequence generation, allocation concealment, blinding participants and personnel, blinding outcome assessment, incomplete outcome data, selective reporting, and other bias. Each risk of bias assessment category ranked selected studies as having “low risk of bias”, “unclear risk of bias”, or “high risk of bias”. The risk of bias summary—review authors' judgements about each risk of bias item for each included analysis, and the risk of bias graph—review authors' conclusions about each risk of bias item presented as percentages across all included studies, were created via the RevMan 5.4.1 computer program [96].

2.5. Data Extraction

The extracted data included the following information: author, year, groups, number of participants, participant characteristics, type of exercises allocated to groups, materials used for exercise interventions, total weeks, sessions, sets, repetitions, measured muscle, measurement device and regions, type of the muscle architectural parameter, and results of the eligible studies.

2.6. Meta-Analysis

Quantitative analyses were completed using the Review Manager (RevMan 5.4.1) program [96]. For an exercise intervention group, a placebo or control group was considered a comparator. As summary statistics, Hedge's (adjusted) g effect size (the standardised mean difference (SMD)) was estimated for each meta-analysis by using RevMan [96]. The

difference between Hedge's (adjusted) g and Cohen's d is that Hedge's (adjusted) g corrects a potential estimation bias when the sample size is smaller than 20 participants [97]. The effect sizes of the exergame interventions were interpreted as small (0.2), medium (0.5), or large (0.8), which were generally used for interpreting the Cohen's d [98] and Hedges' g [99] effect sizes [100].

For a case of a missing standard deviation (SD) from the baseline score, which is commonly seen in continuous data-carrying studies [101], the following formula was used for calculations [101,102]:

$$SD_{change} = \sqrt{SD_{baseline}^2 + SD_{final}^2 - (2 \times r \times SD_{baseline} \times SD_{final})}$$

In this formula, SD_{change} represents the SD of the mean changes from the baseline, $SD_{baseline}$ represents the SD of the pre-test, SD_{final} corresponds to the SD of the post-test, and the r represents the correlations between the SD_{final} and $SD_{baseline}$ measurements.

In the meta-analyses, statistical heterogeneity was calculated via chi-squared (χ^2 , or Chi^2) statistics, and the level of the statistical heterogeneity was assessed by I^2 statistics, which defines the percentage ratio of the variability in effect calculations due to heterogeneity rather than chance [103]. The I^2 values were classified as low (25%), moderate (50%), and high (75%) [104]. A more conservative random effect (RE) model, 95% confidence interval, continuous data, and inverse variance features of a meta-analysis were applied during the quantitative analyses [105]. The RE model was defined as a better tool that accounts for statistical and methodological heterogeneities by a recent meta-analytic study [106].

3. Results

3.1. Study Selection

After the removal of duplicate records, a total of 184 records were independently screened based on titles and abstracts. One hundred seventy-seven records were excluded based on the exclusion criteria, and seven records were included based on the pre-determined eligibility criteria. The seven records and an additional two records, which were retrieved throughout the third database searches, were independently screened based on the full text. Eventually, five studies [107–111] were found eligible and included in this systematic review. The process of selecting eligible studies is presented in the PRISMA 2020 flow chart in Figure 1.

3.2. Quality Assessment of Included Studies

Once the first and second authors had independently assessed the evidence level of both randomised and non-randomised studies via the Downs and Black checklist [92], and the risk of bias of included studies by using The Cochrane Collaboration's tool for assessing risk of bias in randomised trials [95], any disagreements were solved by discussion between the first (N.S.) and second (G.Y.) authors, and the third author (T.Y.) was considered a referee in the case of unsolved disagreements. Consequently, the evidence levels of three studies were detected as having a "fair level" [108,110,111]. The evidence levels of the other studies were assigned the "good level" [107,109]. The quality assessments of each study are shown in detail in Table 1, a risk of bias summary—review authors' judgements about each risk of bias item for each included study is presented in Figure 2, and a risk of bias graph—review authors' judgements about each risk of bias item presented as percentages across all included studies is presented in Figure 3.

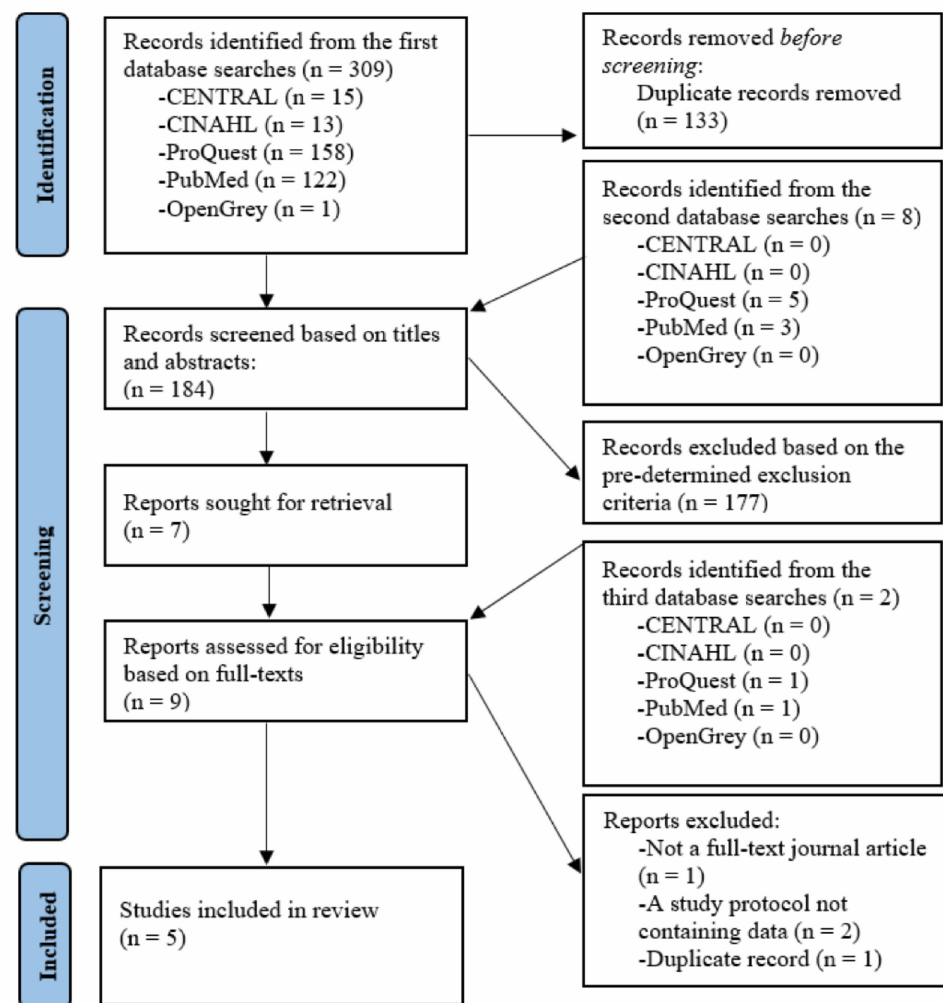


Figure 1. PRISMA 2020 flow diagram.

Table 1. Quality assessment of eligible studies.

		Biesek et al. (2021) [107]	Gallo et al. (2019) [108]	Nambi et al. (2020) [109]	Rodrigues et al. (2018) [110]	Vojciechowski et al. (2021) [111]
Reporting						
Q1	Is the hypothesis/aim/objective of the study clearly described?	1	1	1	1	1
Q2	Are the main outcomes to be measured clearly described in the introduction or methods section?	1	1	1	1	1
Q3	Are the characteristics of the patients included in the study clearly described?	1	1	1	1	1
Q4	Are the interventions of interest clearly described?	1	1	1	1	1
Q5	Are the distributions of principal confounders in each group of subjects to be compared clearly described?	0	0	0	0	0

Table 1. Cont.

		Biesek et al. (2021) [107]	Gallo et al. (2019) [108]	Nambi et al. (2020) [109]	Rodrigues et al. (2018) [110]	Vojciechowski et al. (2021) [111]
Q6	Are the main findings of the study clearly described?	1	1	1	1	1
Q7	Does the study provide estimates of the random variability in the data for the main outcomes?	1	0	1	0	0
Q8	Have all important adverse events that may be a consequence of the intervention been reported?	1	0	0	1	0
Q9	Have the characteristics of patients lost to follow-up been described?	1	1	1	1	1
Q10	Have actual probability values been reported (e.g., 0.035 rather than <0.05) for the main outcomes, except where the probability value is less than 0.001?	1	1	1	1	1
External Validity						
Q11	Were the subjects asked to participate in the study representative of the entire population from which they were recruited?	UTD	UTD	UTD	UTD	UTD
Q12	Were those subjects who were prepared to participate representative of the entire population from which they were recruited?	UTD	UTD	UTD	UTD	UTD
Q13	Were the staff, places, and facilities where the patients were treated representative of the treatment the majority of patients receive?	1	1	1	1	1
Internal Validity—Bias						
Q14	Was an attempt made to blind study subjects to the intervention they received?	0	0	0	0	0
Q15	Was an attempt made to blind those measuring the main outcomes of the intervention?	0	1	1	0	0
Q16	If any of the results of the study were based on “data dredging”, was this made clear?	1	1	1	1	1
Q17	In trials and cohort studies, do the analyses adjust for different lengths of follow-up of patients? Or in case-control studies, is the time period between the intervention and outcome the same for cases and controls?	1	1	1	1	1
Q18	Were the statistical tests used to assess the main outcomes appropriate?	1	1	1	1	1

Table 1. *Cont.*

		Biesek et al. (2021) [107]	Gallo et al. (2019) [108]	Nambi et al. (2020) [109]	Rodrigues et al. (2018) [110]	Vojciechowski et al. (2021) [111]
Q19	Was compliance with the intervention/s reliable?	1	1	1	1	1
Q20	Were the main outcome measures used accurate (valid and reliable)?	1	1	1	1	1
Internal validity—Confounding (selection Bias)						
Q21	Were the patients in different intervention groups (trials and cohort studies), or were the cases and controls (case-control studies) recruited from the same population?	1	1	1	1	1
Q22	Were study subjects in different intervention groups (trials and cohort studies), or were the cases and controls (case-control studies) recruited over the same period of time?	1	1	1	1	1
Q23	Were study subjects randomised to intervention groups?	1	0	1	0	0
Q24	Was the randomised intervention assignment concealed from both patients and health care staff until recruitment was complete and irrevocable?	UTD	0	UTD	0	0
Q25	Was there an adequate adjustment for confounding in the analyses from which the main findings were drawn?	1	1	1	1	1
Q26	Were losses of patients to follow-up taken into account?	1	1	1	1	1
Power						
Q27	Did the study have sufficient power to detect a clinically important effect, where the probability value for a difference resulting from chance is less than 5%?	1	1	1	1	1
Total		21	19	21	19	18
Quality of evidence		Good	Fair	Good	Fair	Fair

Abbreviations: UTD, Unable to determine;
0, no; 1, yes.

	Random sequence generation (selection bias)	Allocation concealment (selection bias)	Blinding of participants and personnel (performance bias)	Blinding of outcome assessment (detection bias)	Incomplete outcome data (attrition bias)	Selective reporting (reporting bias)	Other bias
Biesek et al. (2021)	+	+	?	?	+	+	?
Gallo et al. (2019)	-	-	?	+	+	+	?
Nambi et al. (2021)	+	+	?	+	+	+	+
Rodrigues et al. (2018)	-	-	?	-	+	+	?
Vojciechowski et al. (2021)	-	-	?	-	+	+	?

Figure 2. Risk of bias summary: review authors' judgements about each risk of bias item for each included study (created via RevMan 5.4.1).

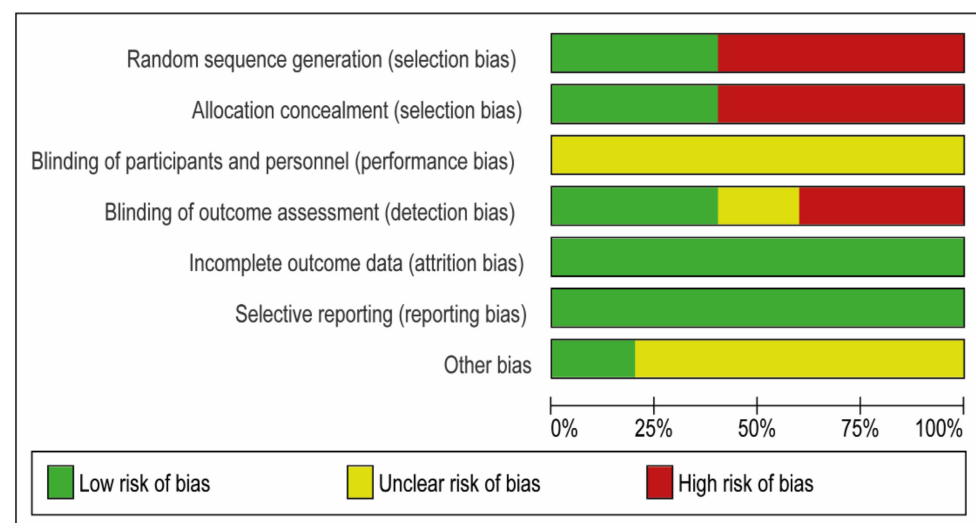


Figure 3. Risk of bias graph: review authors' judgements about each risk of bias item presented as percentages across all included studies.

3.3. Characteristics of Included Studies

Participants' age, population type, physical activity levels, and intervention and measurement characteristics of the included studies are illustrated in Table 2. Two studies [107,109] were classified as randomised controlled, and three studies [108,110,111] were classified as non-randomised controlled studies. Two studies [107,108] examined the effects of twelve-week exergame interventions on the medial gastrocnemius muscle architecture, while two studies [109,110] focused on the effects of twelve-week exergame interventions on the quadriceps femoris muscle cross-sectional area of community-dwelling older women. Additionally, one study [110] assessed the impacts of a twelve-week exergame training on the hamstring cross-sectional area of community-dwelling older women, and another study [109] measured the effects of four weeks of exergame intervention on the multifidus muscle thickness and the paraspinal muscle cross-sectional area in football players.

Table 2. Characteristics of included studies.

Study (Year)	Groups, Number of Participants (n), Type of Exercises Allocated to Groups	Participants' Characteristics (Population, Age, Physical Activity Levels)	Material(s) for Exercise(s)	Total Weeks, Sessions, Sets and Repetition of Exercises	Measured Muscles for the Architectural Parameter(s)	Measurement Device and Region(s)	Type of Muscle Architectural Parameter(s)
Biesek et al. (2021) *	-Exergames training group (ETG) (n = 14): Performed 12 weeks of exergames training. -Control group (CG) (n = 15);	-Community-dwelling older women. -Age: ETG = 71.2 ± 4.2 , CG: 70.04 ± 3.9 . -Physical activity level: Not specified.	-Nintendo Wii Fit Plus® + balance platform.	-Total of 12 weeks, two sessions per week, each session was approximately 50 min.	-Medial gastrocnemius muscle.	-A 2D B-mode US. 30% and 40% of the distance between the popliteal line and lateral malleolus of the fibula.	-Fascicle length (FL). -Muscle Thickness (MT). -Pennation angle (PA).
Gallo et al. (2019)	-Exercise Group (EG) (n = 22): Performed 12 weeks of virtual dance exercise. -Control Group (CG) (n = 20): Kept their daily lifestyle.	-Community-dwelling older women. -Age: EG = 69.3 ± 3.7 , CG = 70.3 ± 5.6 . -Physical activity level: Moderately active.	-Dance Central game for Xbox 360® and Kinect.	-Total of 12 weeks, three sessions per week, each session was 40 min.	-Medial gastrocnemius muscle.	-A 2D B-mode US. 20%, 30%, and 40% of the distance between lateral condyle of the tibia and lateral malleolus of the fibula.	-Fascicle length (FL). -Muscle Thickness (MT). -Pennation angle (PA).
Nambi et al. (2020)	-Virtual Reality Training Group (VRT-G) (n = 12): Performed virtual reality-based balance training for core stability muscles using the ProKin system. -Combined Physical Rehabilitation Group (CPR-G) (n = 12): Performed a rehabilitation protocol that particularly emphasised balance exercises at home by using a Swiss ball. -Control Group (Control-G) (n = 12): Performed conventional balance training. -Additionally, all participants underwent 20 min hot-pack therapy and therapeutic US (1.5 W/cm ² intensity 1 Mhz frequency) and prescribed home-based exercise protocol (10 reps, 2 sets per day for 4 weeks).	-Male football players. -Age: VRT-G = 21.3 ± 2.6 , CPR-G: 21.8 ± 2.2 , Control-G: 20.9 ± 2.8 . -Physical activity level: University football players with chronic lower back pain.	-The ProKin system for the VRT-G. -A Swiss Ball for the CPR-G.	-Total of 4 weeks. -VRT-G: 5 sessions per week; each session was 30 min. -CPR-G: 10 repetitions, 3 sets, 5 sessions per week. -Control-G: 10–15 repetitions per day, 5 sessions per week.	-Multifidus and paraspinal muscles.	-MRI and Diagnostic US. -Paraspinal muscles (psoas major, quadratus lumborum, multifidus and erector spinae) measured at L3–L4 levels by using an MRI. -The left and right multifidus muscle at L4 and L5 levels by using a US.	-Cross-sectional area (CSA) of the paraspinal muscles. -MT of the multifidus.

Table 2. Cont.

Study (Year)	Groups, Number of Participants (n), Type of Exercises Allocated to Groups	Participants' Characteristics (Population, Age, Physical Activity Levels)	Material(s) for Exercise(s)	Total Weeks, Sessions, Sets and Repetition of Exercises	Measured Muscles for the Architectural Parameter(s)	Measurement Device and Region(s)	Type of Muscle Architectural Parameter(s)
Rodrigues et al. (2018)	Intervention Group (IG) (n = 22, 10 fallers, 12 non-fallers): Completed a video-game dance training program. Control Group (CG) (n = 25, 12 fallers, 13 non-fallers): Kept their daily routine.	-Community-dwelling older women. -Age: IG fallers = 69.8 ± 4.3 , IG non-fallers = 68.9 ± 3.3 , CG fallers = 73.6 ± 5.4 , CG non-fallers = 68.7 ± 4.8 . -Physical activity level: Low to moderate physical activity levels.	-Dance Central game for Xbox 360® and Kinect.	-12 weeks, 3 sessions per week, each session was ~40 min.	-Hamstrings and quadriceps femoris.	-MRI -Measurements were taken from the mid-point between the femur's inferior condyle border and the greater trochanter.	-CSA of the hamstrings and quadriceps femoris.
Vojciechowski et al. (2021)	Training Group (TG) (n = 21): Performed 12 weeks of a virtual dance training program. Control Group (CG) (n = 21): Kept their daily routine.	-Community-dwelling older women. -Age: TG = 69 ± 4 , CG = 71 ± 5 . -Physical activity level: At least moderately active.	-Dance Central game for Xbox 360® and Kinect.	-12 weeks, 3 sessions per week, each session was ~40 min.	-Quadriceps femoris.	-MRI -Measurements were taken from the mid-point between the anterior superior iliac spine and the femoral condyle.	-CSA of quadriceps femoris.

* For this study of Biesek et al. (2021), the other groups investigating effects of supplementation and training combinations were not mentioned in the table for solely examining the effects of exergames.

3.4. Meta-Analyses

In total, four studies were included in the meta-analyses [107,108,110,111]. Firstly, two studies [110,111] were included in the meta-analysis assessing the effects of twelve-week virtual dance training (Dance Central game for Xbox 360® and Kinect) on the quadriceps femoris cross-sectional area in community-dwelling older women (Figure 4). Secondly, study subgroups of another study [110] were included in the meta-analysis measuring the effects of twelve-week virtual dance training (Dance Central game for Xbox 360® and Kinect) on the hamstrings cross-sectional area in community-dwelling older women (Figure 5). In both cases, twelve-week virtual dance training (Dance Central game for Xbox 360® and Kinect) showed a medium effect on the improvement of hamstrings ($g = 0.55$, 95% CI $(-0.03, 1.14)$, $I^2 = 0\%$) and the quadriceps femoris ($g = 0.58$, 95% CI $(0.17, 1.00)$, $I^2 = 0\%$) muscle cross-sectional areas without statistical heterogeneity in community-dwelling older women.

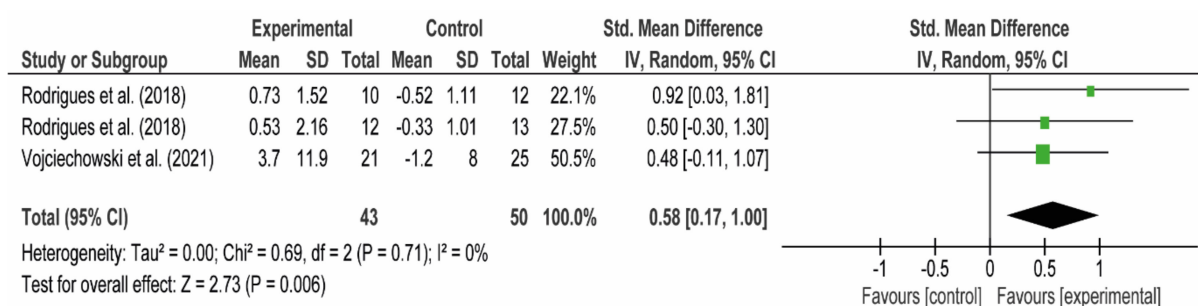


Figure 4. The effects of twelve weeks exergames on the quadriceps femoris muscle cross-sectional area in community-dwelling older women. Note: The first line of Rodrigues et al. [110] represents fallers, and the second line represents non-fallers. This forest plot was created via RevMan [96].

Thirdly, two studies [107,108] were included in meta-analyses assessing the impacts of twelve weeks of exergame interventions (Nintendo Wii Fit Plus® + balance platform [107] and Dance Central game for Xbox 360® + Kinect [108]) on the gastrocnemius muscle architectural parameters, including fascicle length, muscle thickness, and pennation angle, in community-dwelling older women. Individually or as combined in the meta-analyses,

these exergames had no positive medium or large effects on increasing medial gastrocnemius fascicle length ($g = -0.40$, 95% CI $(-1.10, 0.31)$, $I^2 = 74\%$ (Figure 6a)), muscle thickness ($g = -0.04$, 95% CI $(-0.41, 0.33)$, $I^2 = 25\%$ (Figure 6b)), or pennation angle ($g = -0.08$, 95% CI $(-0.40, 0.23)$, $I^2 = 0\%$ (Figure 6c)).

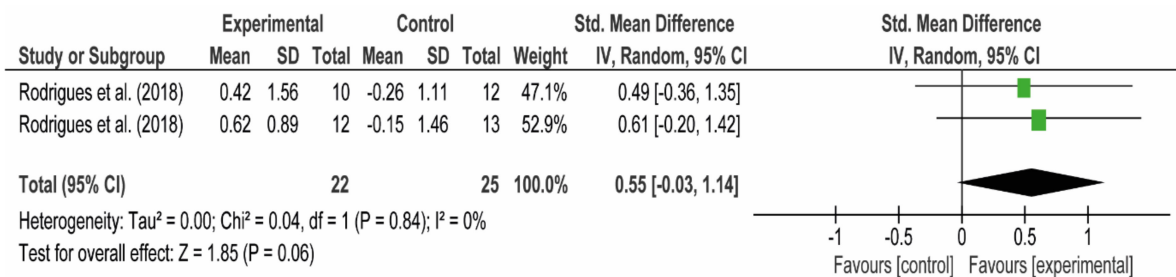
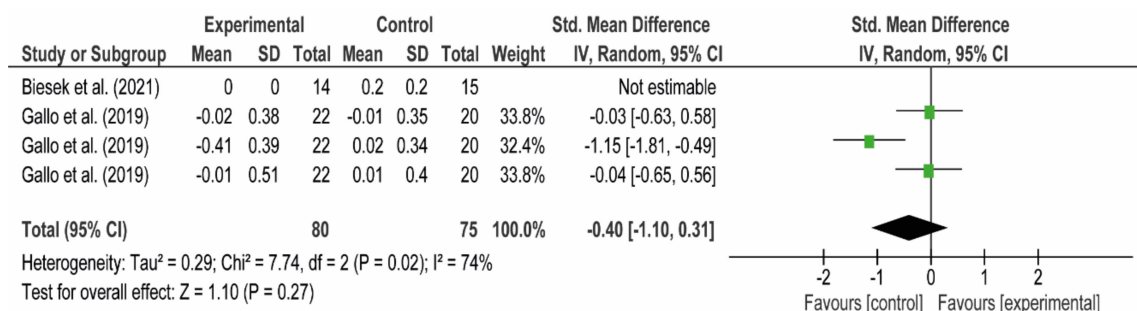
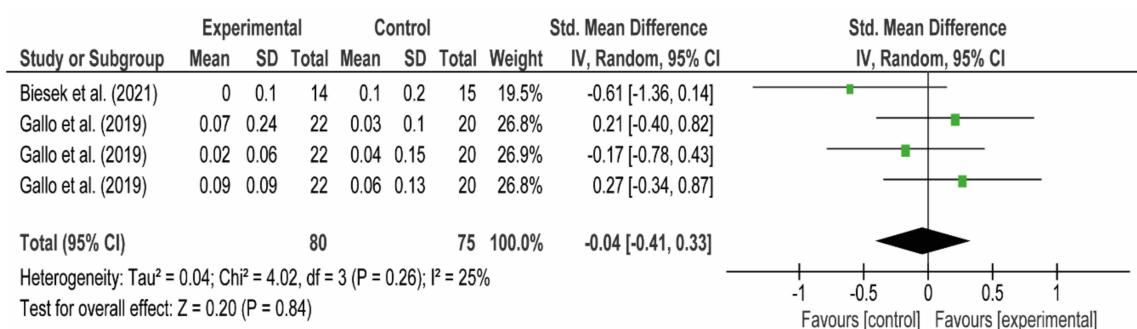


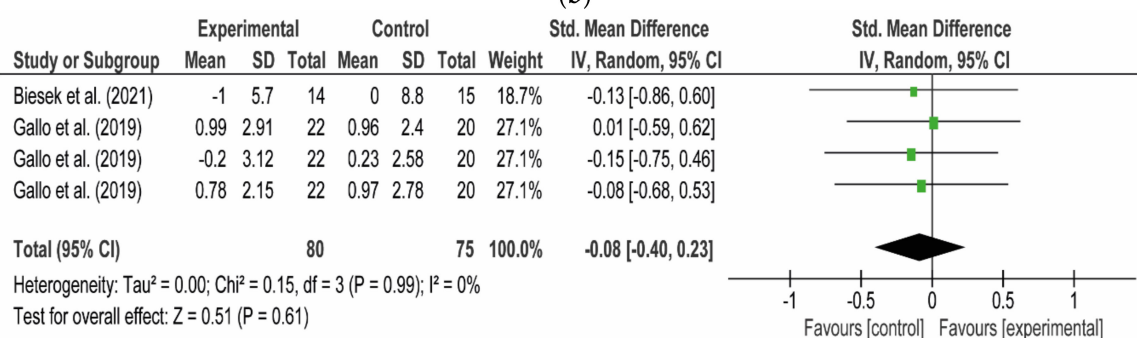
Figure 5. The effects of twelve weeks of exergames on the hamstring muscle cross-sectional area of community-dwelling older women. Note: The first line of Rodrigues et al. [110] represents fallers, and the second line represents non-fallers. This forest plot was created via RevMan [96].



(a) *



(b)



(c)

Figure 6. The effects of twelve weeks of exergames on the medial gastrocnemius muscle architecture in community-dwelling

older women: (a) fascicle length; (b) muscle thickness; (c) pennation angle. * In this meta-analysis, the given data in the study of Biesek et al. [107] was not calculable by RevMan [96]. Note: The first, second, and third Gallo et al. in each forest plot respectively represent the measurements taken from 20%, 30%, and 40% distances in the relevant study [108]. These forest plots were created via RevMan [96].

Lastly, one study [109] was not included in the meta-analyses due to the absence of other methodologically similar studies investigating the same topic. In this study, Nambi et al. [109] examined the effects of four-week virtual reality balance training (the ProKin system) on multifidus muscle thickness and paraspinal muscles, including multifidus again, cross-sectional area in university-level football players with chronic lower back pain.

As a result, Nambi and colleagues reported significant increments in the paraspinal muscle cross-sectional areas (psoas major: 25.58–26.19%, quadratus lumborum: 41.67–46.81%, multifidus: 44.23–43.40%, erector spinae: 14.55–14.63%) and 6.4–8.46% increments in multifidus muscle thickness (Supplementary Table S3).

4. Discussion

To the authors' knowledge, this systematic review is the first systematic review focusing particularly on the effects of exergames on the architectural parameters of the skeletal muscles in humans. Based on studies identified to have a fair level of quality [110,111], 12 weeks of virtual dance exercises (Dance Central game for Xbox 360®) has a medium effect on increasing the quadriceps femoris muscle cross-sectional area. Likewise, 12 weeks of virtual dance exercises (Dance Central game for Xbox 360®) has a medium effect on increasing the quadriceps femoris muscle cross-sectional area based on a study with fair-level quality [110]. Additionally, a good-quality study [109] pointed out that four weeks of virtual balance training (via using the ProKin system) was significantly more effective than home-based balance training with the Swiss ball and conventional balance training in increasing paraspinal muscle size at the L3–L4 level and multifidus muscle size at the L4–L5 level in football players with chronic lower back pain. More specifically, the four weeks of virtual balance training [109] led to 14.55–46.81% increments in the paraspinal muscle cross-sectional areas (psoas major: 25.58–26.19%, quadratus lumborum: 41.67–46.81%, multifidus: 44.23–43.40%, erector spinae: 14.55–14.63%) and 6.4–8.46% increments in multifidus muscle thickness (Supplementary Table S3). On the other hand, meta-analyses measuring the impacts of twelve weeks of exergame interventions (Nintendo Wii Fit Plus® + balance platform [107] and Dance Central game for Xbox 360® + Kinect [108]) on gastrocnemius muscle architectural parameters, including fascicle length, muscle thickness, and pennation angle, in community-dwelling older women could not detect any positive medium or large effects of these exergames on the medial gastrocnemius muscle architectural parameters based on the fair–good-level studies [107,108].

From the perspective of the effects of 12 weeks of virtual dance exercises (Dance Central game for Xbox 360®), medium effects on the increase in muscle size of the quadriceps femoris and hamstrings of community-dwelling older women were detected by the meta-analyses of this study. Moreover, the effect size of 12 weeks of virtual dance exercises on quadricep muscle size increments in community-dwelling older and faller women was large ($g = 0.92$) (Figure 4). When considering older people, falling is one of the major reasons for mortality, loss of independence, or severe health problems [112–114]. Thirty per cent of community-dwelling people 65 years old or older fall every year [115,116]. Small muscle size was defined as an indicator of a higher risk of falls in community-dwelling older people [39,40,117,118]. Therefore, 12 weeks of virtual dance exercises (Dance Central game for Xbox 360®) can be used as a complementary therapy in fall prevention programs for the elderly due to its medium to large effects on increasing cross-sectional areas of the hamstrings and quadriceps femoris.

Additionally, Nambi and colleagues [109] found significantly favourable increments in the paraspinal and multifidus muscle sizes from the virtual balance training as compared

to combined physical rehabilitation, which included balance exercises using a Swiss Ball, or conventional balance training. Previously, balance training with a Swiss Ball was considered the golden standard for balance training and enhancing the strength of core muscles [119]. However, four weeks of virtual reality balance training using the ProKin system led to percentage increments approximately two times higher in the cross-sectional areas of the individual paraspinal muscles (erector spinae, multifidus, psoas major, and quadratus lumborum) than four weeks of combined physical therapy, which included a Swiss Ball balance training (Supplementary Table S3). Hence, virtual reality balance training might be used as an alternative tool to improve the sizes of the paraspinal muscles. More studies may wish to confirm the effects of virtual reality balance training on core muscles. Furthermore, lower back pain is prevalent in many sports [120] and might reduce the size of core muscles, including multifidus and psoas major [121]. Decreased multifidus muscle size has previously been found to be associated with lower extremity injuries in sports [23–27]. Therefore, a future randomised controlled trial can examine the effects of virtual balance training on the multifidus muscle size in athletes without lower back pain.

Despite the comprehensive database searches, the main limitation of this systematic review is its use of only five eligible studies. Having more eligible studies might have allowed this systematic review to have more precise conclusions about more skeletal muscles. However, to the authors' knowledge, this systematic review retrieved all the relevant studies. Additionally, all the eligible studies were published in the last three years. This fact could indicate that the quantity of studies investigating the effects of exergames on muscle architecture might increase in the future. Therefore, this systematic review might be updated in the future in order to explore the effects of exergames on the architecture of other muscles. An additional limitation of this study is the lack of publication bias assessments or meta-regression analyses since there were less than ten studies used. The Cochrane Handbook for Systematic Review of Interventions clearly states that there should be at least ten studies in a meta-analysis for detecting publication bias in funnel plots or meta-regression analyses [122]. Thus, differences in the training interventions and populations are considered to be other confounding factors in the meta-analysis. Future studies might be conducted on the effects of exergames on other muscle architectures in order to obtain an overall idea of the effectiveness of exergames in improving the architectural parameters of human skeletal muscles.

5. Conclusions

Twelve weeks of virtual dance exercise (Dance Central game for Xbox 360®) showed a medium effect on improving the hamstrings and the quadriceps femoris muscle cross-sectional area of community-dwelling older women. Additionally, a four-week virtual balance training program (the ProKin System) led to significant increments in the size of paraspinal muscles. However, one twelve-week virtual dance exercise program (Dance Central game for Xbox 360®) [108] or another twelve-week exergame training program (Nintendo Wii Fit Plus® + balance platform) [107] did not show any medium or large effects on the increase of the medial gastrocnemius muscle architectural parameters in community-dwelling older women. These results should be interpreted cautiously due to the small number of eligible studies.

In conclusion, twelve weeks of virtual dance exercise (Dance Central game for Xbox 360®) might be used as a complementary therapy in fall and fragility prevention programs for community-dwelling older women due to its positive effects on increasing hamstrings and quadriceps femoris muscle sizes. Additionally, a four-week virtual balance training program (the ProKin System) can be included in rehabilitation programs for chronic lower back pain in university-level football players to increase the paraspinal muscle cross-sectional area in football players with chronic lower back pain. Moreover, the exergames which showed positive effects on increasing muscle sizes, e.g., the virtual dance game and the virtual balance training, can also be used as complementary therapies for home-based

rehabilitation programs. Consequently, more studies are needed to have an overall idea of the effects of exergames on muscle architectural parameters in humans.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/app112110325/s1>, Table S1: The PRISMA 2020 Statement Checklist, Table S2: Database Search Histories, Table S3: Training-induced percentage changes in muscle architectural parameters in the study of Nambi and colleagues.

Author Contributions: N.S. was involved in designing the review, independently screened the citations obtained through database searches, independently performed the quality assessment of the eligible studies, independently extracted data from eligible studies, and contributed to the writing process of the manuscript. G.Y. was involved in designing the review, performed the database searches, independently screened the citations obtained through database searches, independently performed the quality assessment of eligible studies, independently extracted data from eligible studies, and contributed to the writing process of the manuscript. T.Y. was involved in designing the review, acted as a referee in the case of an unsolved discussion. Conceptualization, N.S., G.Y., and T.Y.; methodology, N.S., G.Y., and T.Y.; software, N.S. and G.Y.; formal analysis, N.S. and G.Y.; formal analysis, N.S. and G.Y.; investigation, N.S. and G.Y.; resources, N.S. and G.Y.; data curation, N.S. and G.Y.; writing—original draft preparation, N.S. and G.Y.; writing—review and editing, N.S. and G.Y.; visualization, N.S. and G.Y.; supervision, T.Y. All authors have read and agreed to the published version of the manuscript.

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